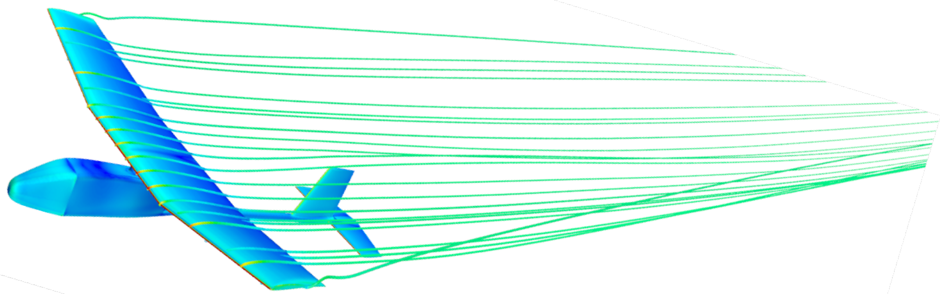
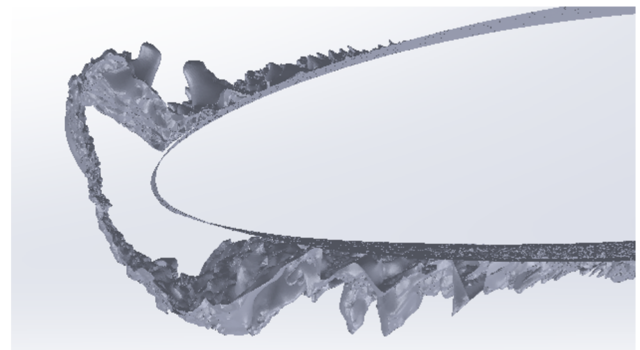
Airborne science driven CFD of small UAS:
Scalable airframe and ice accretion simulations





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AMS Seminar Series
NASA Ames Research Center
March 22nd 2018

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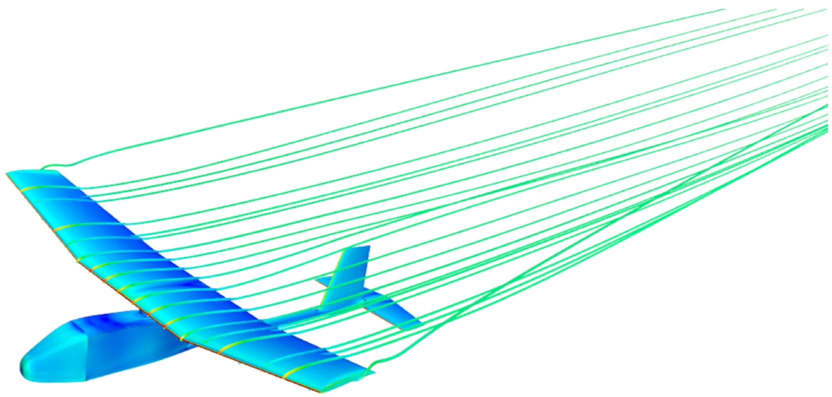
Earth Science Drivers for CFD Analysis

- Quick validation of numerous but usually small changes to aircraft in order to accommodate a wide variety of unique science payloads
  - Addition of a pod-mounted payload; modified nose or fuselage to carry payload
  - Effect of adding NACA scoop or external pylon for gas sensing probe
  - Interaction of prop wash and ground effects on payload sampling
- Simulation of frequently-modified UAS
  - For new payload airworthiness certification
  - Pitot tube study, stability study, etc
  - Evaluate tradeoffs enabled by modularity
- Small UAS in all environments
  - In potential or actual icing-conditions
  - Icing, crosswinds, etc have outsize effect



Project Goals and Outcomes

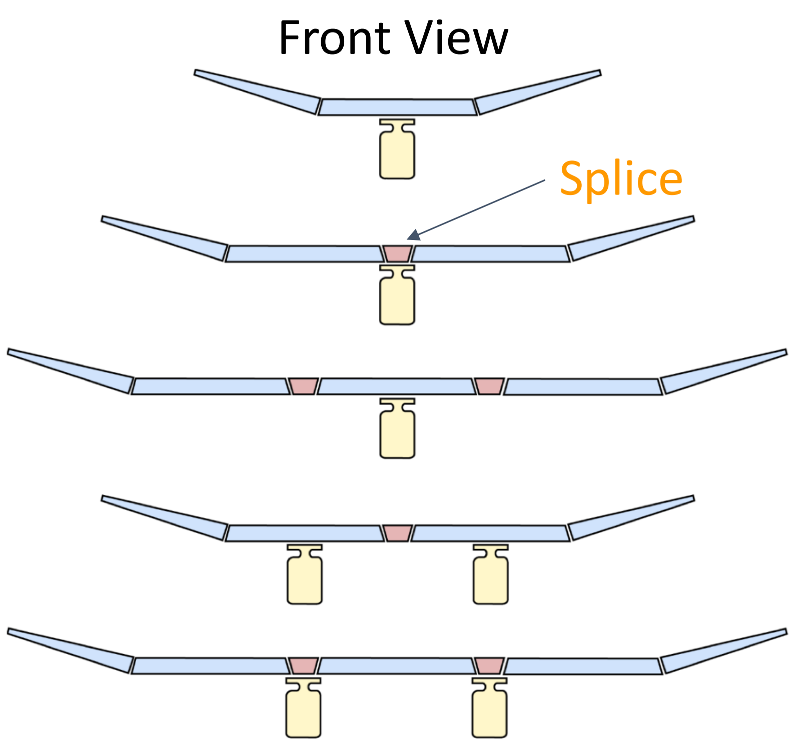
- Leverage access to unique tools in support of Airborne Science
  - Supercomputer resource allocation, straightforward request via HEC ebooks
  - Licenses to STAR-CCM+ and open source tools
- Document provisioning process and CFD setup for the next PI
- Performance of FrankenRaven and tradeoff study
- CFD on suspected pitot tube location for airspeed indication error
- Performance of dual-fuselage FrankenRaven with instrument pod
- Ice accretion CFD on three small UAS under different cloud conditions
- Validate icing CFD and wind tunnel at very low airspeeds
- Development and documentation of useful scripts and macros

Project 1: CFD of Modular Small UAS

- Modularity for different airframe configurations
  - Multiple fuselage and wing modules
  - Variety of payloads and mission profiles
  - Even simple modularity creates a complex tradeoff space
- Advantages compared to non modular UAS
  - Can be reconfigured on-the-spot
  - Straightforward building and logistics
  - Simplified repairs in the field with spare modules
  - Possible to optimize the airframe around the payload
- Supports variety of ConOps (Concept of Operations)
- Small class I aircraft used to demonstrate/validate

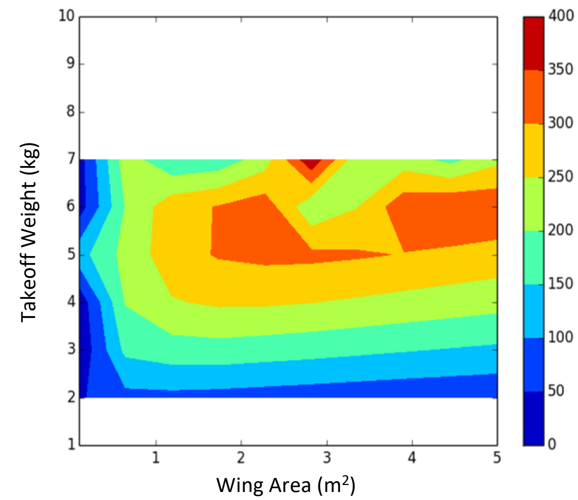
Modular UAS Concept: Fixed Wing

- Piecewise scalable fuselage, wing, battery, thrust, payload, and control surfaces
- Demonstrate the feasibility of modularity with UAS owned by ARC
- The UAS is segmented to facilitate fitting into a backpack
- Use as raw material for new aircraft
  - Connect wing segments with splice
  - Splice fabricated with 3D printing
  - Maximum splice count limited



Modular Framework Enables Tradeoff Space

- Modular aircraft is a new paradigm compared to fixed-configuration aircraft for science-driven applications; follows CubeSat model
- Modular aircraft opens up a new tradeoff space for mission design
- Studies in 2013 in 2014 showed that one of the most powerful variables in the aircraft performance tradeoff space is wingspan
- Number of wings (biplane, triplane)
- Battery count (also increases reliability)
- Payload weight (and ballast if any)
- Control surfaces (size, number, moment arm)
- Propulsors (number of thrust modules)



Spring 2017 Stanford Workshop

Considerations for Small UAS Flight Analysis

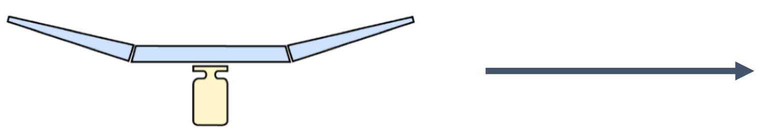
- Low speed operation: Mach 0.04
- FrankenRaven: Chord D = 8.0” [203 mm]
- Low Reynolds number flight conditions
    - Between 130k to 400k
    - Large effective wing surface area at low velocity
    - Viscous drag is dominant, pressure drag is less of a factor
- Multiple configurations
    - Entails multiple envelopes of performance
    - Multiple payload capabilities to study

$$\mathrm{Re} = \frac{\rho v D}{\mu}$$

$\mu = 1.822\times10^{-5}$ Pas

V = 10 m/s to 30 m/s

$\rho = 1.225\ \mathrm{kg/m^3}$

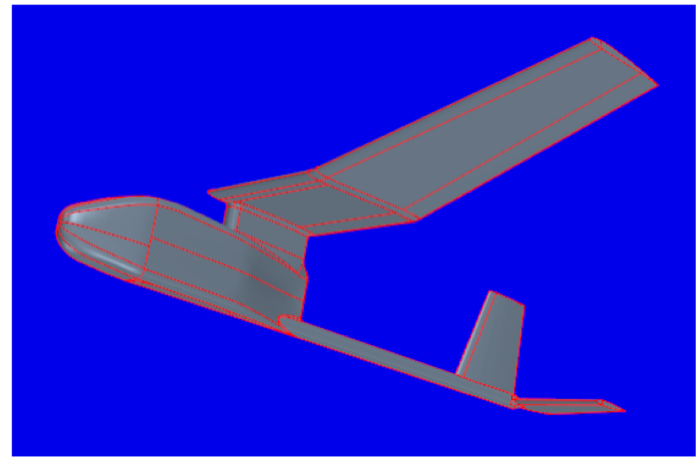


OEM (Span = 1.3 m)

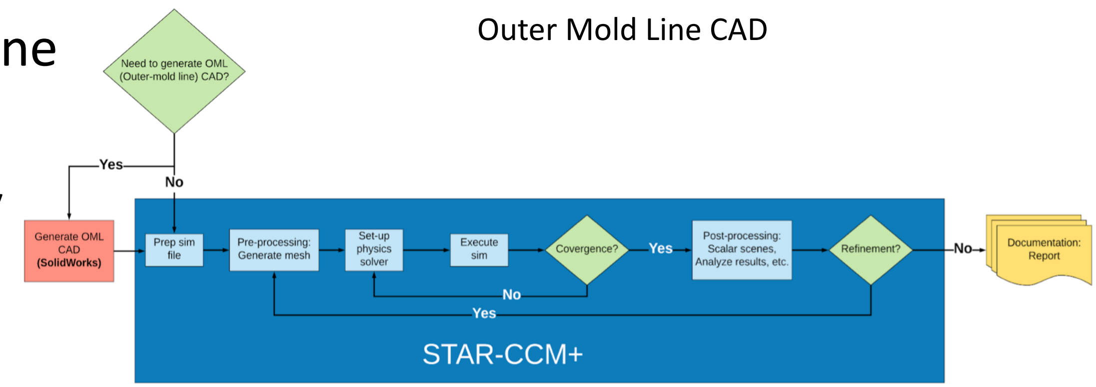
Largest Configuration (Span = 2 m)

Workflow - FrankenRaven

- Convert assembly CAD to OML
- STAR-CCM+
    - Utilized built-in solver and mesh tools
- Steady State Reynolds Averaged Navier-Stokes
- Spalart-Allmaras turbulence modeling
    - Low airspeed
    - Expected minimal separation
- Hemispherical domain
- Mirror symmetry about the XZ plane
    - Set up for utilizing same mesh across wide range of velocities and AoA
    - 30 m radius,~200 chord lengths away

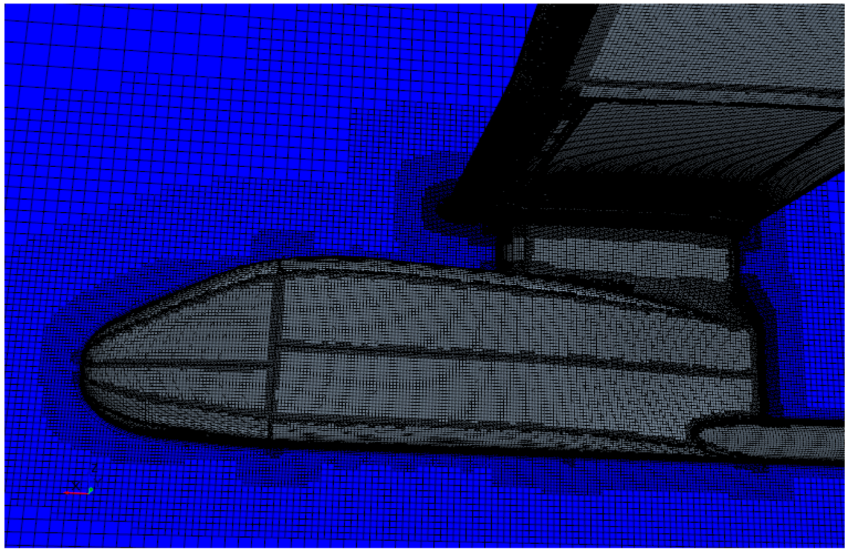


Outer Mold Line CAD



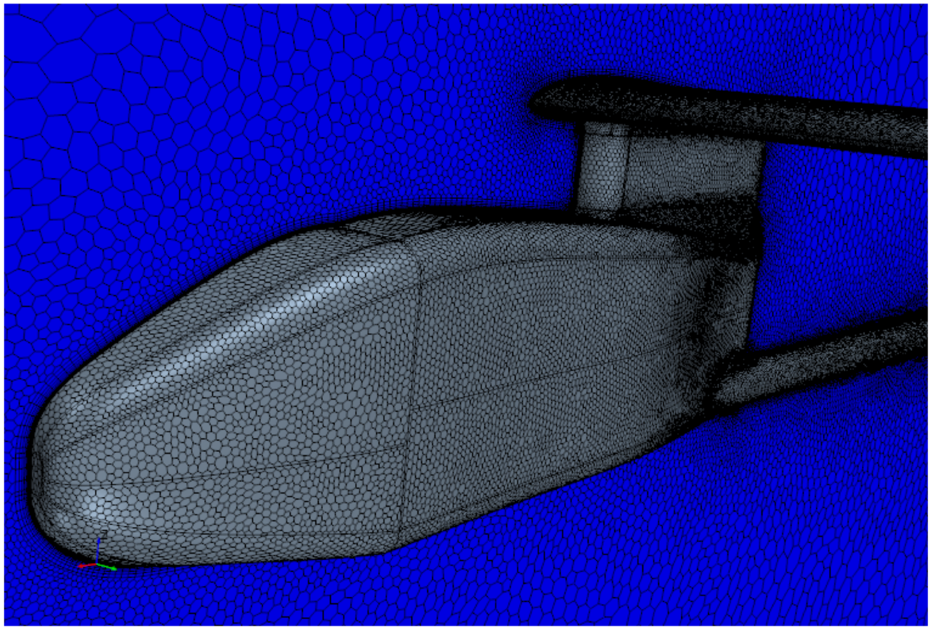
Meshing Approach 1: Trimmer

- Trimmer mesh (STAR-CCM+)
  - Unstructured
  - Majority of cells are exact cubes
  - ~12 million cells to simulate FrankenRaven
- Computationally efficient to both mesh and solve
- Difficult to capture blended areas e.g. the wing-to-fuselage pylon on the small UAS
  - Numerous small radius-of-curvature features
  - Accurate modeling demands high local cell count
- Was labor-intensive to get a high fidelity mesh



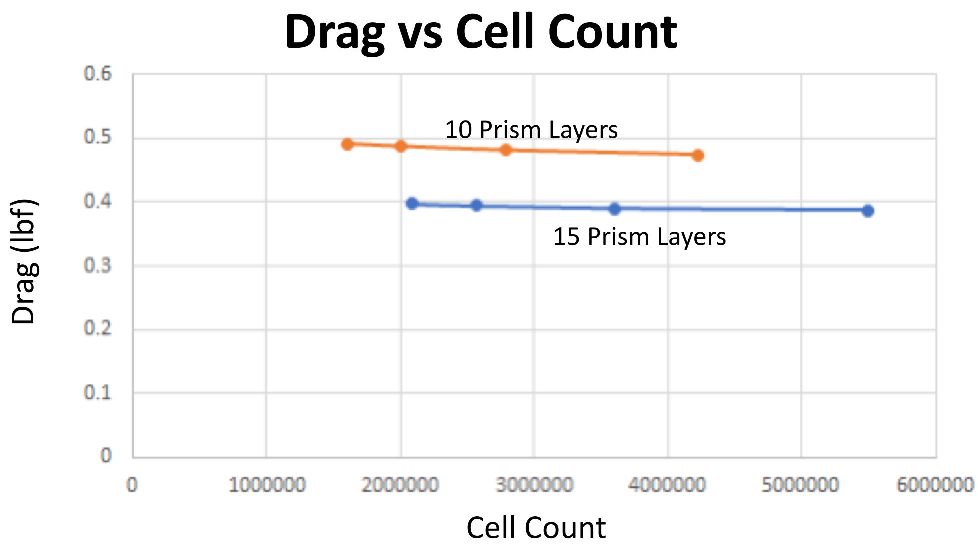
Meshing Approach 2: Polyhedral

- Polyhedral mesh (STAR-CCM+)
    - Unstructured
    - Cells are 3D polyhedrons with variable face count and arbitrary angles
    - ~3 million cells to simulate FrankenRaven
- Computationally efficient solving
    - Similar residual quality
    - Solved in half the time compared to trimmer
    - Smaller file size
- Lesson learned: polyhedral more efficient for our application



Mesh Convergence

- Important for sweeps
  - Minimize cell count/computation
  - Large effects for large sim sweeps
- Parameters of Interest
  - Base size
  - Local cell size
  - Prism layer attributes
- Change in key parameters
  - Lift and drag
  - Residuals
  - Solver time
- Also tested at high and low AoA and airspeed for worst case scenario



States to Simulate

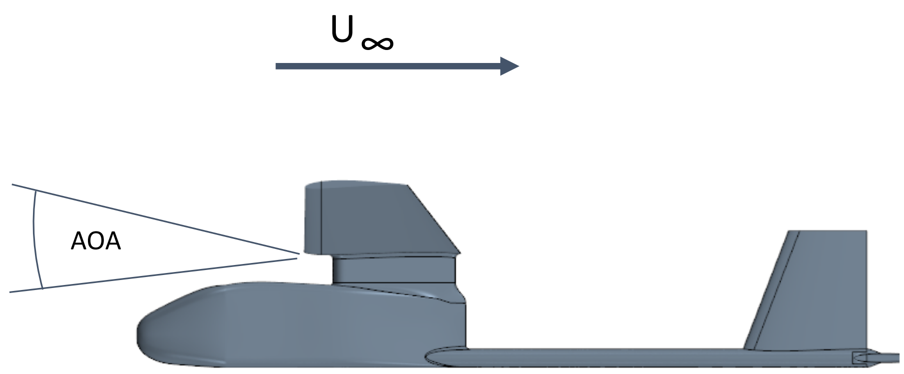
- Solve for constant given climb rate
- Optimize for maximum time on station (minimum power consumption, maximum efficiency, usually just above stall speed)
- Solve for a constant given cruise velocity (constant altitude) equilibrium
  - Thrust must equal drag
  - Lift greater than or equal to aircraft weight
  - Flow has not stalled yet

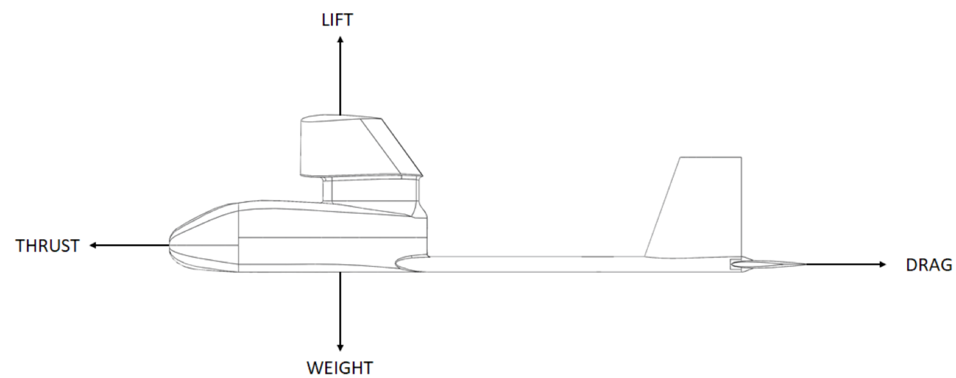
THIS PRESENTATION

- Optimize for maximum distance (~ maximum velocity)
- Glide conditions (for FRRB)
- Maneuvers and landing (g-loading for FRRB)

Simulation Sweeps

- 5 configurations
  - Minimize cell count/computation
  - Save time for large sim sweeps
- AoA from -10 to 20
  - Similar to XFOIL and UIUC database
  - Capture zero lift condition
  - 2 degree increments
- Post-processing
  - MATLAB and Java macros for exporting
  - Linear trends for lift and drag
  - Center of pressure for stability





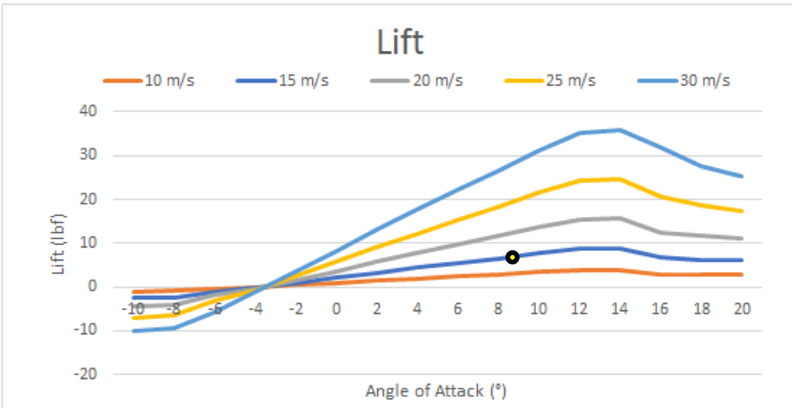
Thrust and Range Calculations

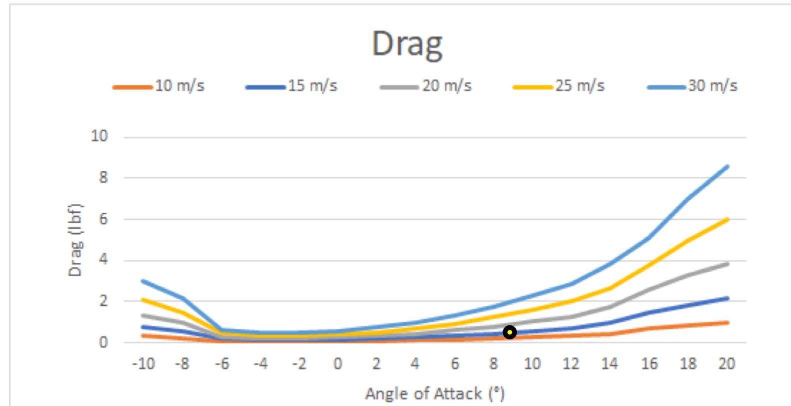
- Dynamic thrust used as approximation for this study
  - Used for rough thrust calcs in radio control aircraft
  - Function of pitch, RPM, and airspeed
- Equivalent drag used for power required
  - 85% efficiency
- Thrust as a function of propeller specifications, RPM, and airspeed
- Calculations done assuming no margin
  - Margin needs to be included for safety

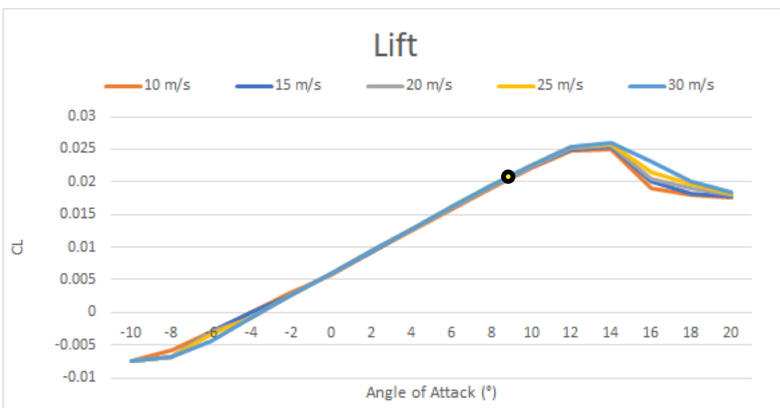
$$Power = Drag * Velocity$$

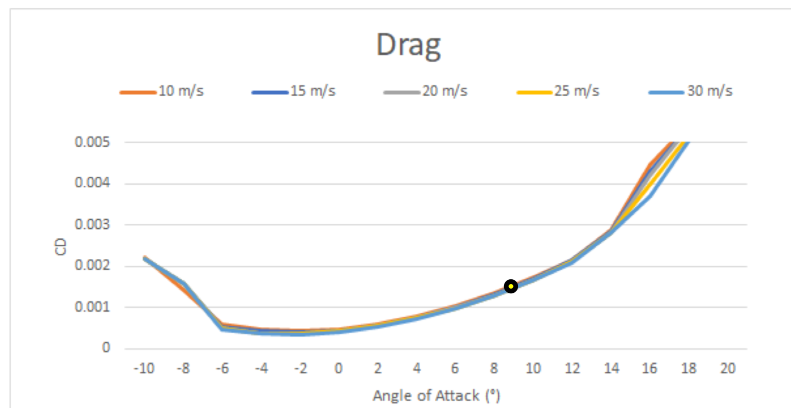
$$Flight\ Time = \frac{Voltage * Capacity}{Power}$$

Points of Equilibrium (OEM)



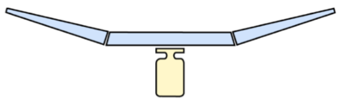
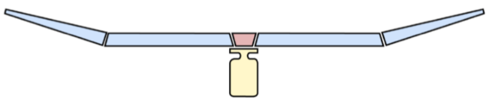
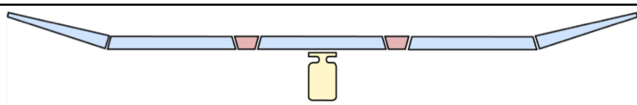
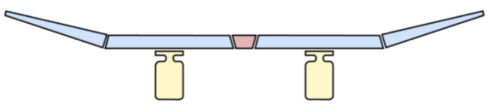




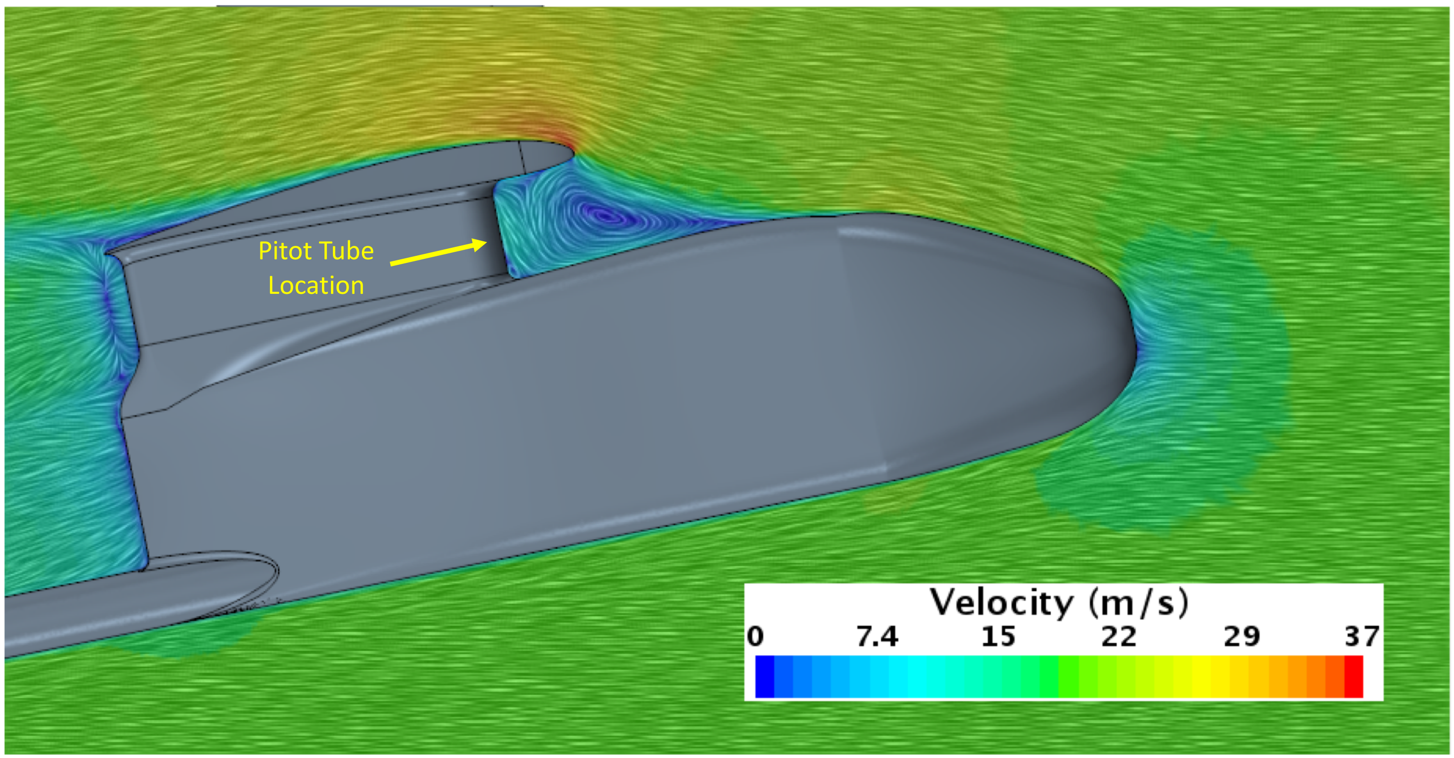


Payload Capabilities from Equilibrium Points

(*For dual-fuselage configurations, indicated margins are for a 2.67 lb payload)

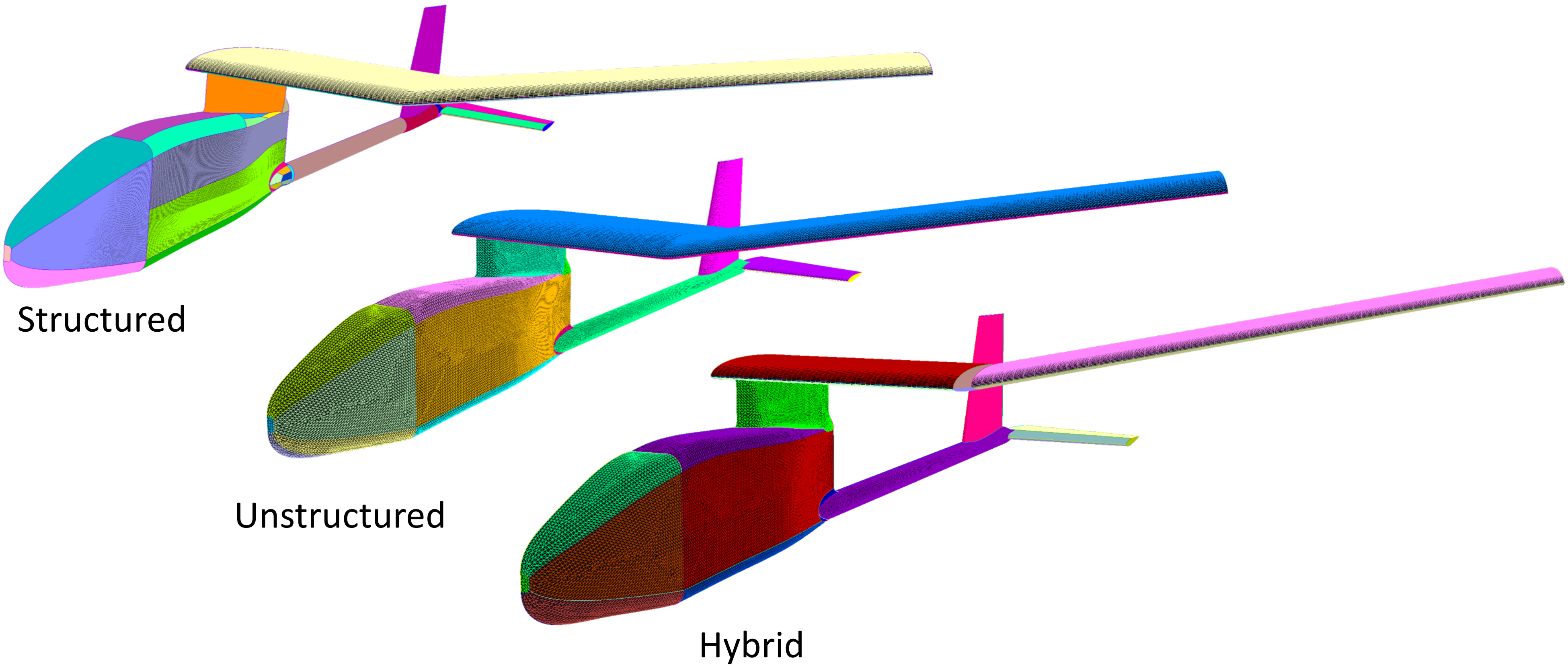
Configuration	AOA	Velocity (m/s)	Lift (lbf)	Payload* (lb)	Range (km)	Time (min)
	8.3	15	6.7	2.5	27.6	31
	10.5	15	12.1	7.3	27.6	31
	3.4	15	9.1	3.7	27.6	31
	8.8	15	11.4	6.1 (56% margin)	27.6	31
	8.0	15	14.8	7.9 (66% margin)	27.6	31

Pitot Tube Turbulence



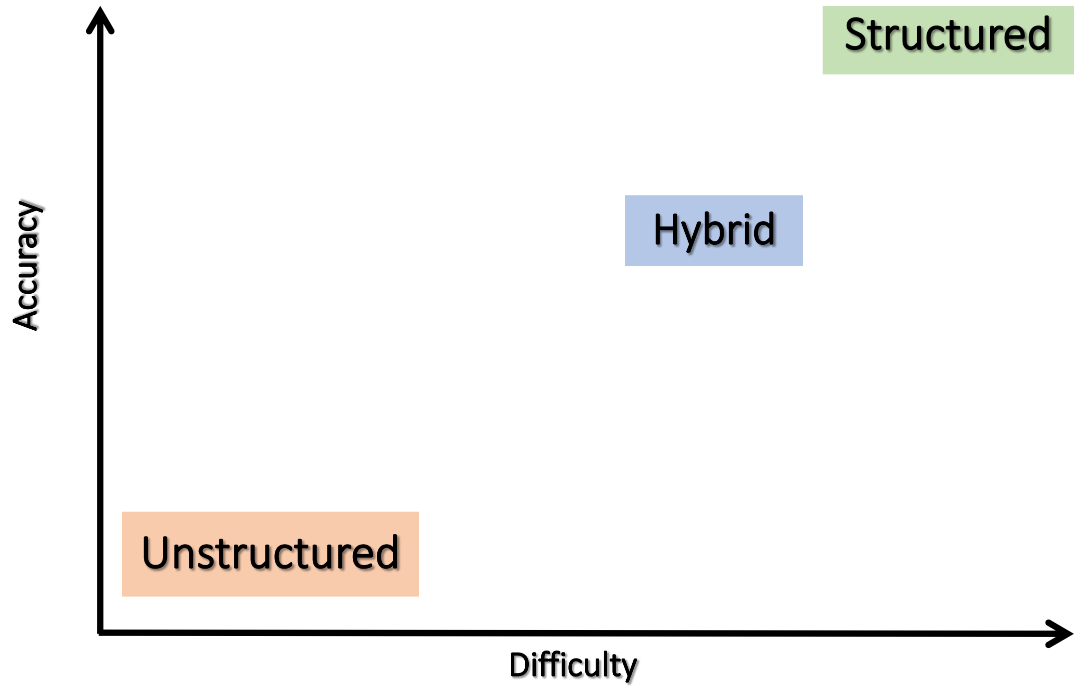
May explain autopilot issues when climbing at high AoA

Meshing Alternative



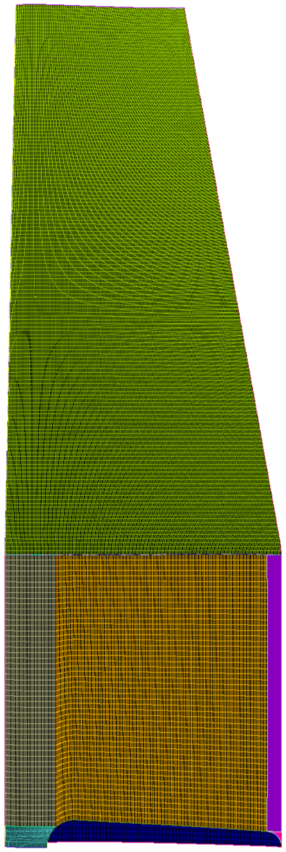
Meshing Alternative

Structured	Unstructured	Hybrid
Low cell count	High cell count	Low cell count
Pre-processing is time consuming	Pre-processing is inexpensive	Pre-processing varies depending on geometry
Hexes comprise of quads	Tets comprised of tris	Compromised of tets, hexes, prisms, and pyramids
~ 1.78 million cells	~ 6.2 million cells	~ 2.8 million cells

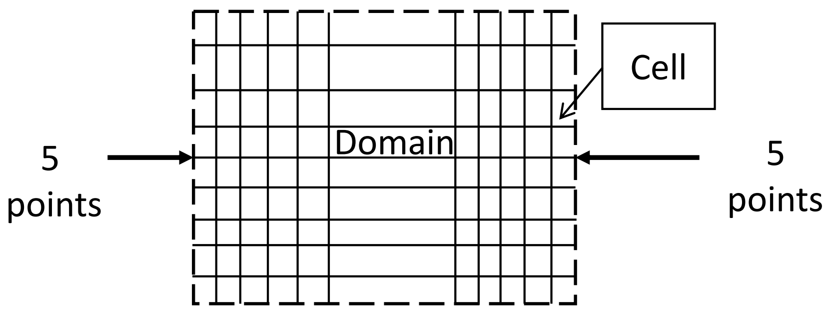


Modified from: Tim Baker, *"Mesh generation: Art or Science?"*, Progress in Aerospace Sciences 2005

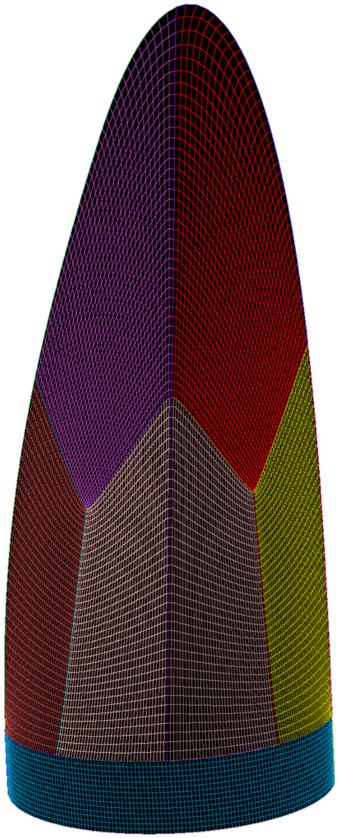
Structured Mesh



Wing section

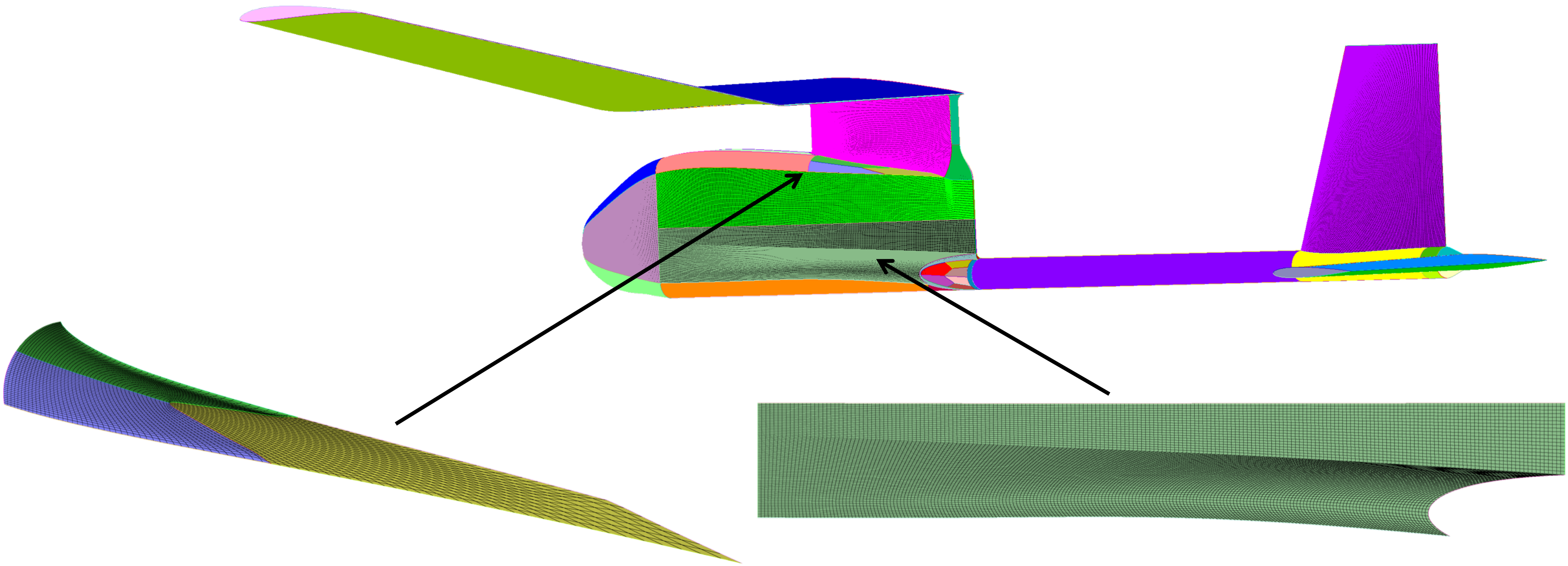


- Opposite edges have to match on the domain
- Each domain is colored differently
- Main goal is to drive cell count down



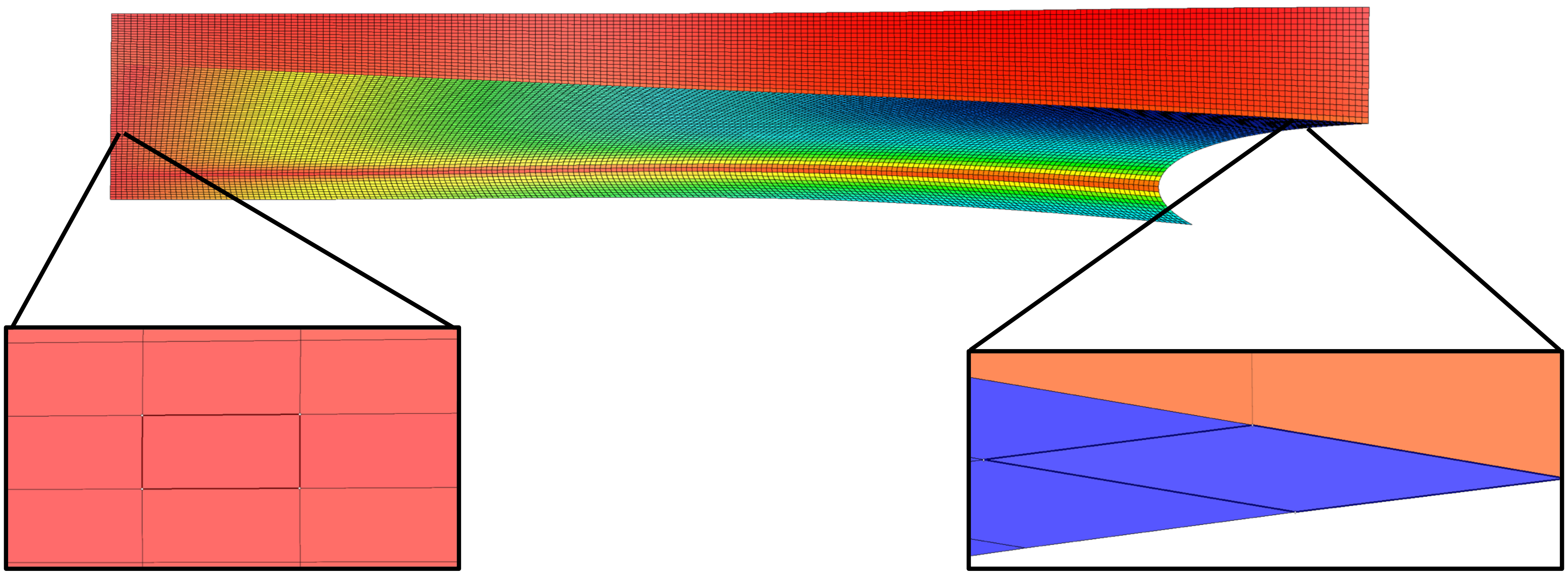
Tailboom – partial view

Structured Mesh



High skewness

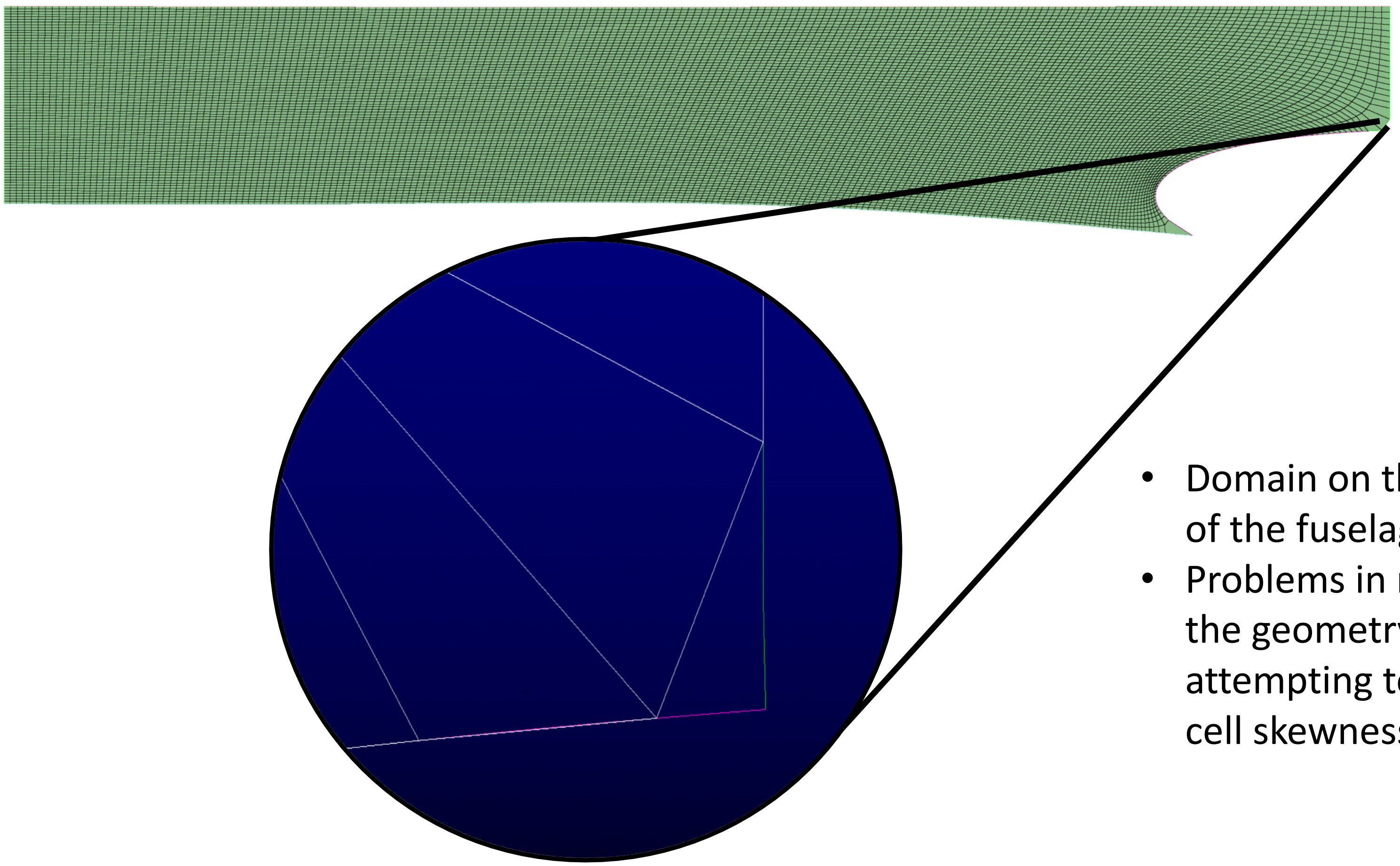
Structured Mesh



Maximum included angle

Minimum included angle

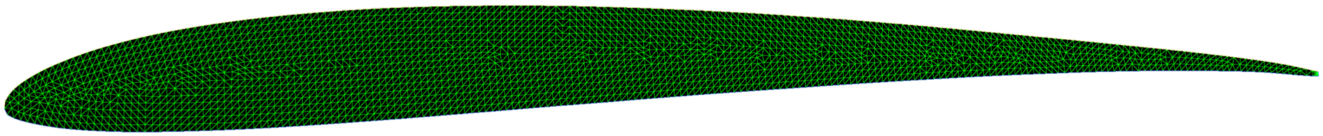
Structured Mesh



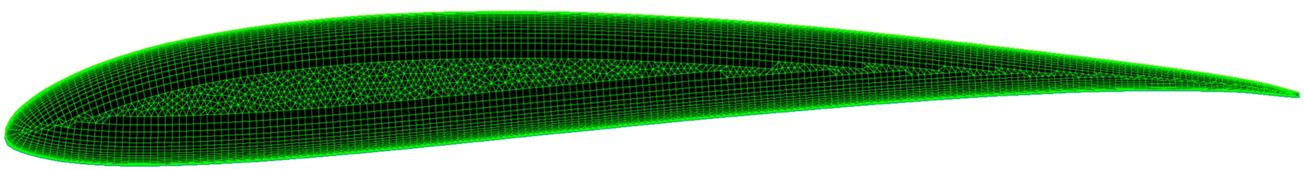
- Domain on the section of the fuselage
- Problems in recovering the geometry while attempting to resolve cell skewness

Hybrid Mesh

- T-Rex is an anisotropic tetrahedral extrusion method developed by Pointwise
- It is a highly automated and robust technique for generating unstructured boundary layer meshes for complex geometries
- Helps with resolving high curvature surfaces
- Reduces time in generating the volume mesh

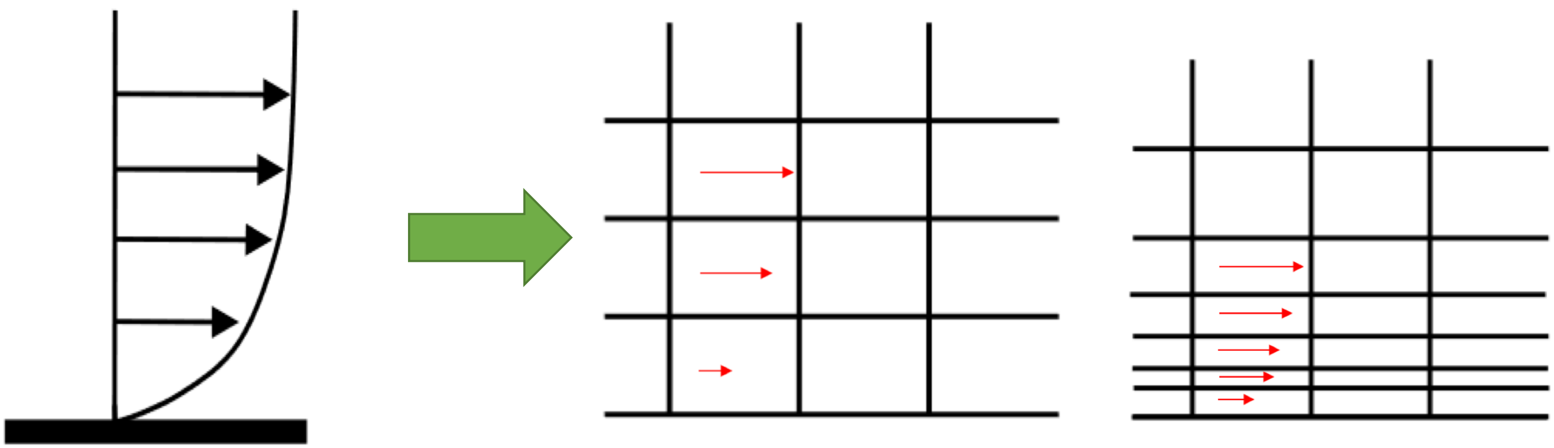


Without T-Rex



With T-Rex

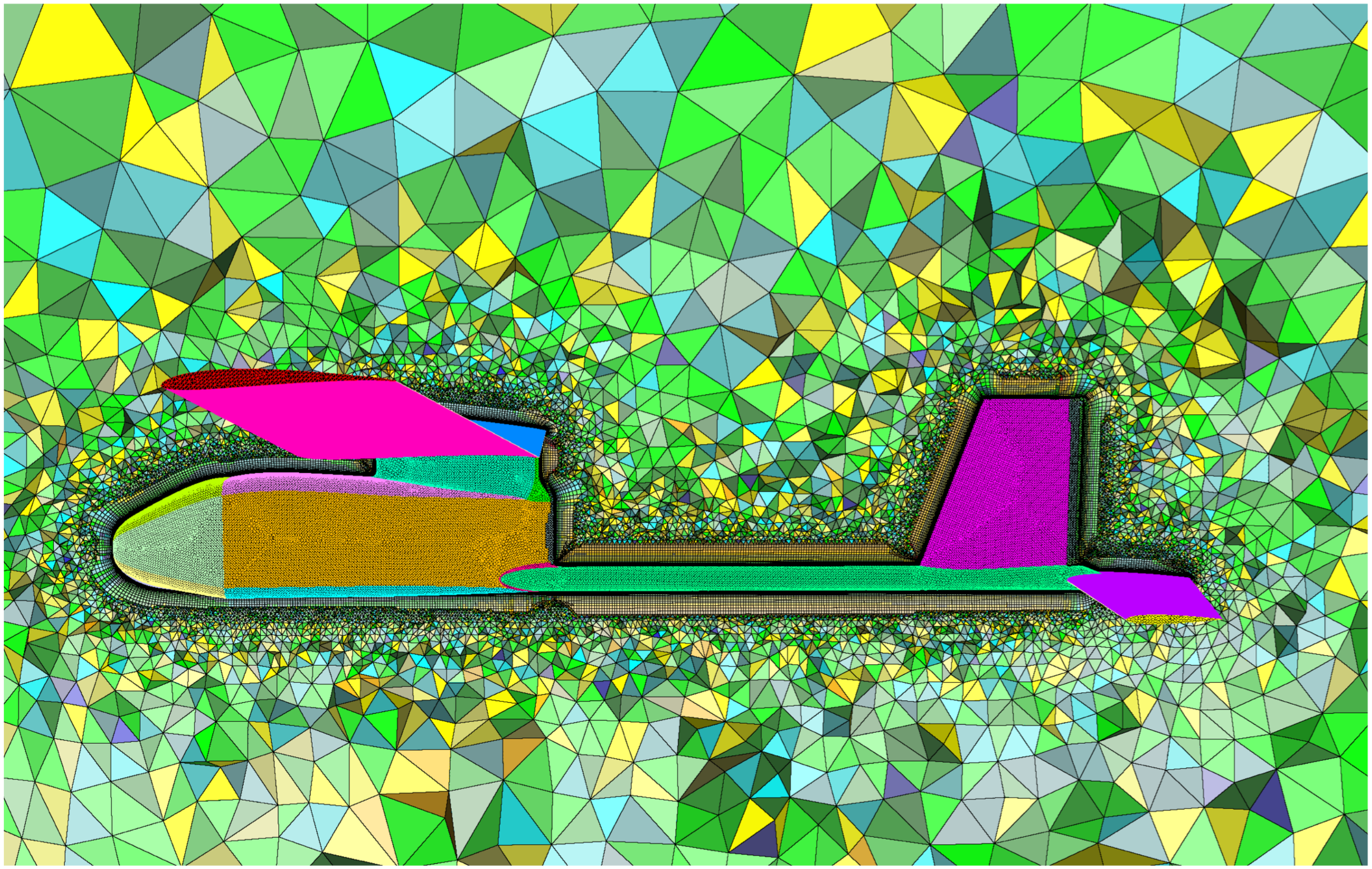
Hybrid Mesh



Inadequate resolution near the wall

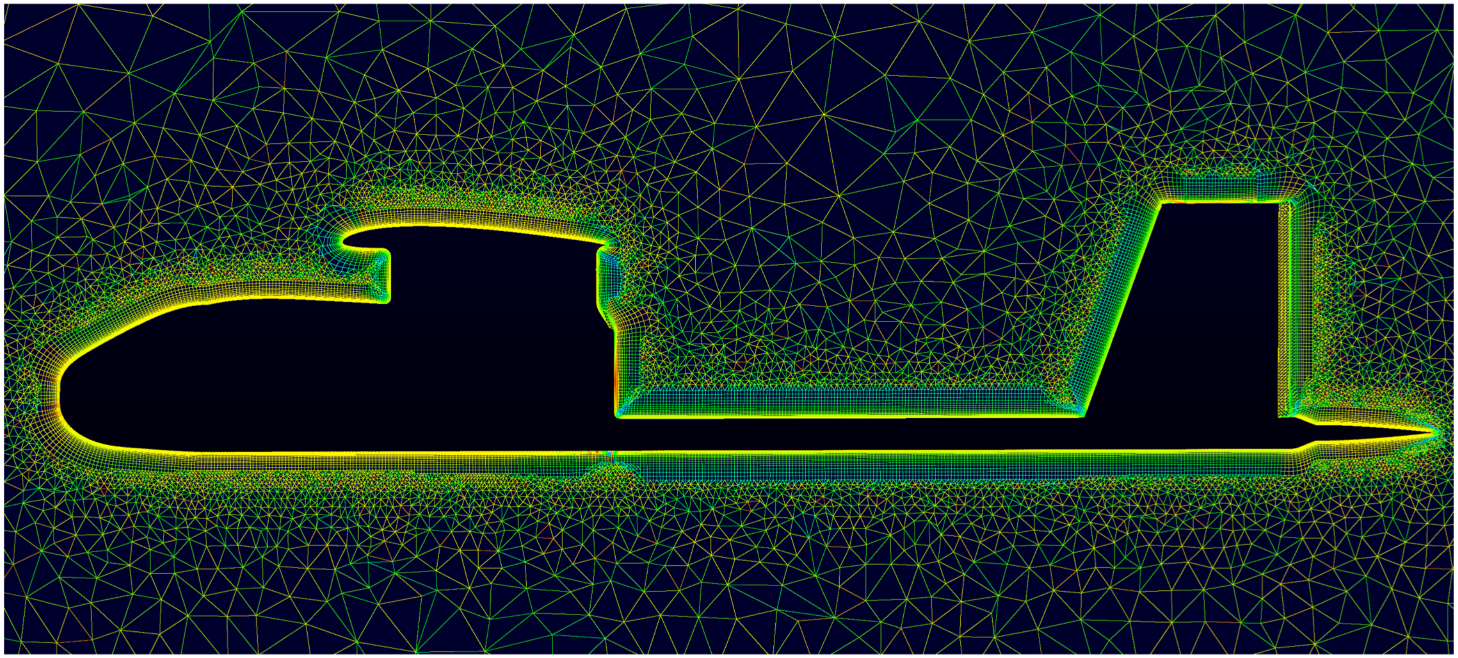
Better quality in resolving the flow features

Hybrid Mesh



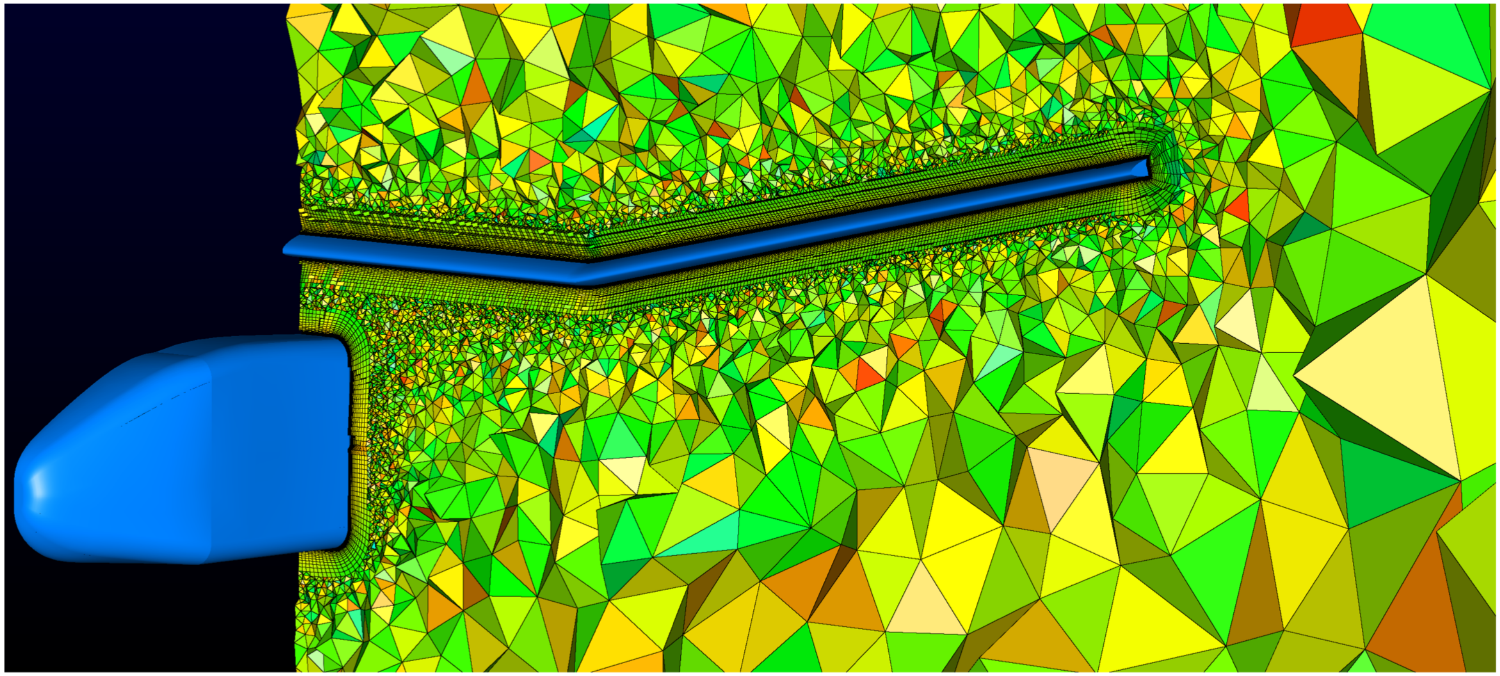
Hybrid Mesh

- Better control of cell size transition with the boundary decay parameter
- Increase boundary decay to prevent erratic jumps in cell size
- Quality cell transitions translates to a more accurate modeling of the flow



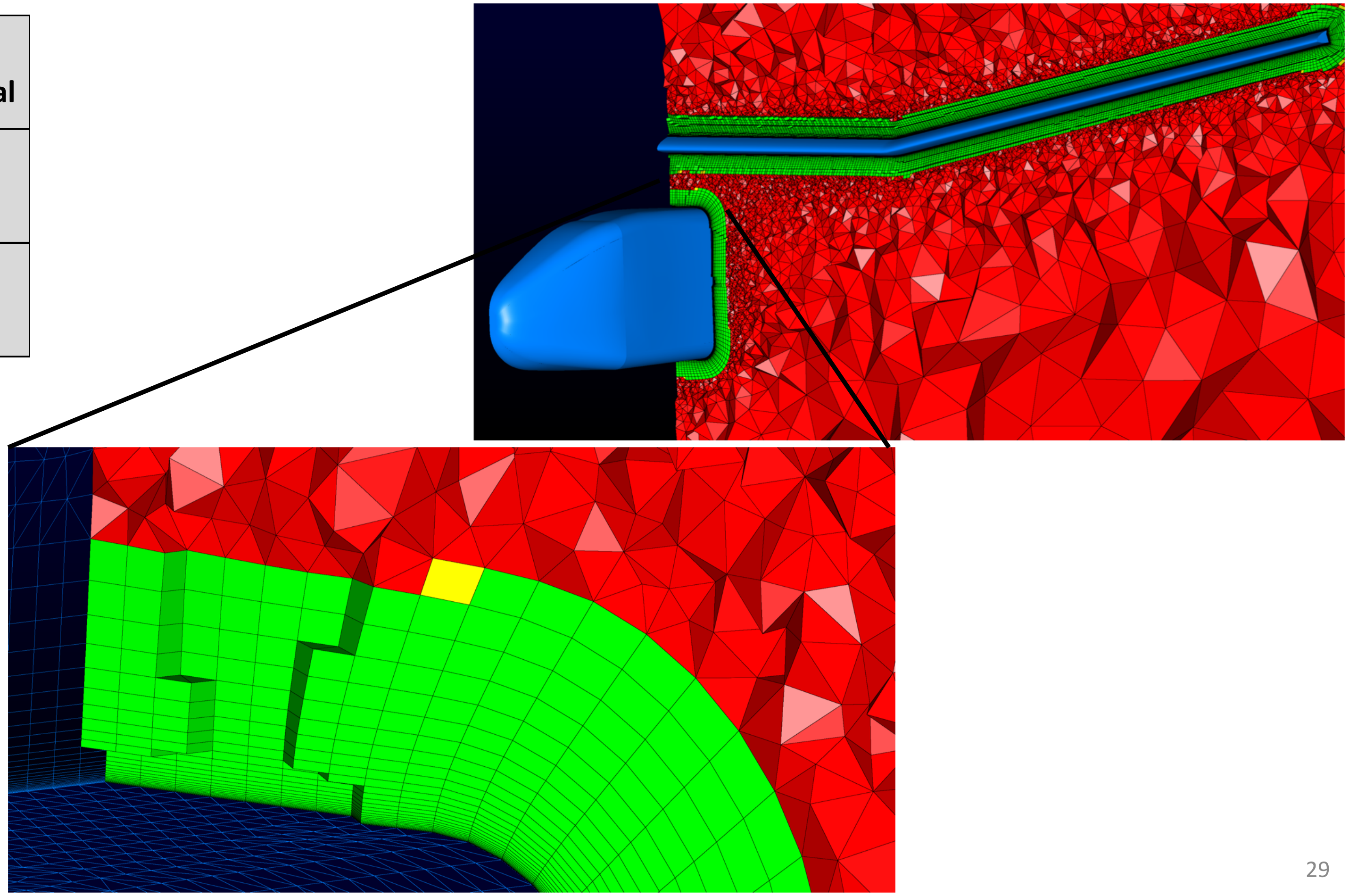
Hybrid Mesh

- Volume mesh in the unstructured block
- Made up of tetrahedrals, pyramids, and prisms
- Generated using T-Rex



Hybrid Mesh

	Tetrahedral
	Pyramid
	Prism

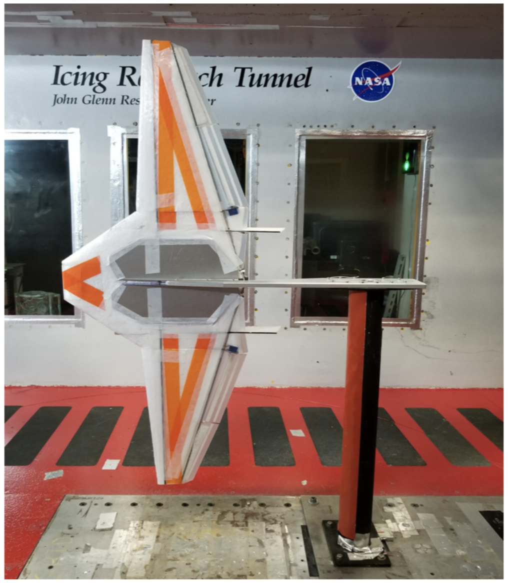


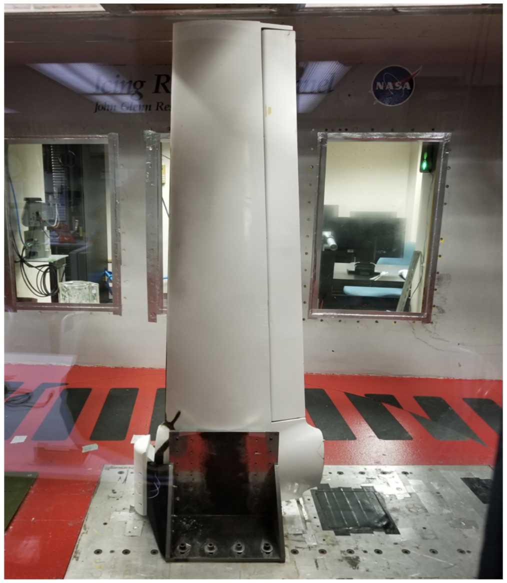
Future Considerations

- More equilibrium points
  - Every configuration has a range of steady flight conditions
  - Each range holds key information to flight capabilities
- Further stability analysis
  - How wingspan affects ease of control
  - Simulate lateral conditions
- Simulate flutter and aero-elasticity
- Smaller sweep increments
- Validation
  - Test steady level conditions
  - Static and dynamic thrust tests
- Concept extensible to larger aircraft

Part 3: Aircraft Icing of Low Speed Small UAS

- Test three small UAS in the Icing Research Tunnel to characterize ice accretion at different flight and icing conditions
- Validate LEWICE3D ice accretion research code for low speed small UAS
- Develop and investigate methodologies of quantitative comparison between experimental and simulation ice shape data





Why UAS?

- Lot more interest in Arctic Regions (Climate Change, Trade Routes, Geopolitics)
- More and more common now as their operating costs are much cheaper
- Able to maneuver in more extreme environments
- Are expendable, and do not risk safety of pilots


Motivation: SIERRA Incident

- 2013 - NASA SIERRA Aircraft lost engine power due to potential icing in Alaska

sUAS Icing vs Large Aircraft Icing

- Icing Research Tunnel Testing at NASA Glenn since 1944
- Our test was the first time UAS was in the IRT
- Weight of ice added in proportion to weight of UAS is much bigger
- More drastic change in performance characteristics
- Large aircraft fly fast enough where the aerodynamic forces form the shape of the ice
- Small UAS fly at a speed where gravity may have to be taken into account in ice formation models (not currently in LEWICE3D code)

Test Articles

DataHawk

- Designed/manufactured by University of Colorado
- Electric Motor Flying Wing, Pusher Propeller
- Used by DOE at Oliktok Point, Alaska
- Collect measurements of lower atmospheric properties
- Looking to develop de-icing systems

ArcticShark

- Designed/manufactured by Navmar Applied Sciences Corporation
- Internal combustion engine, pusher propeller
- Weather-tolerant version of TigerShark
- Airborne atmospheric research drone to measure radiative, aerosol, and cloud properties
- Produces 4000 W, 2500 W dedicated to payload

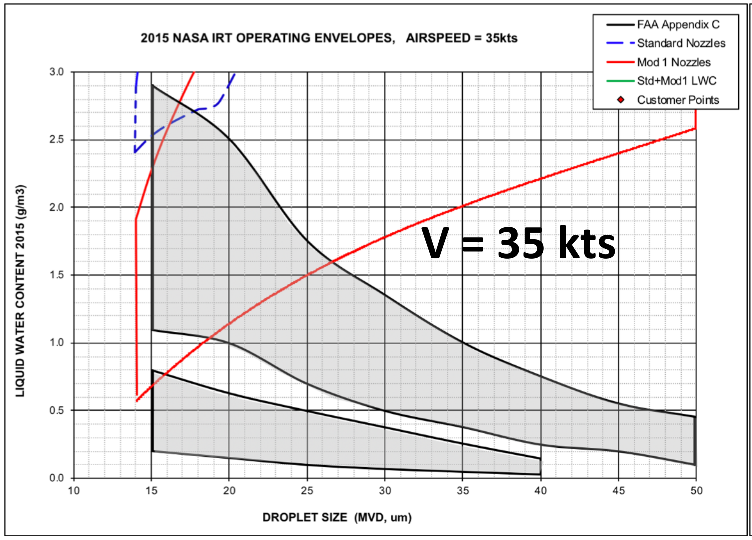
Outlaw SeaHunter

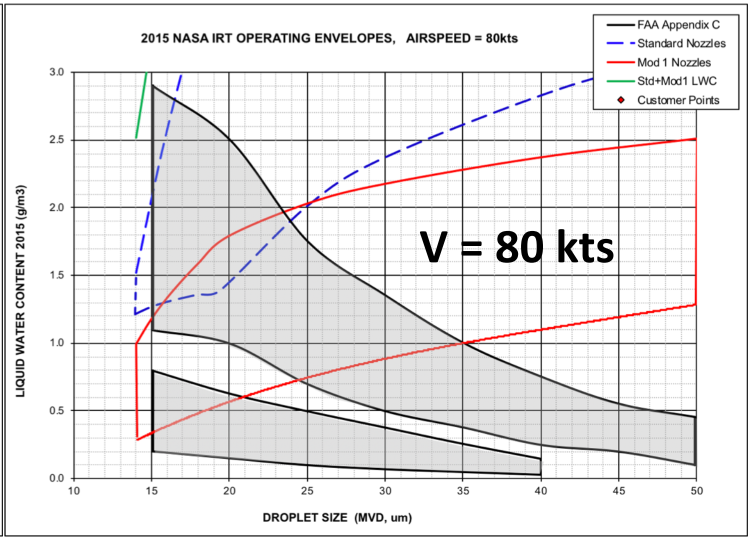
- Designed/manufactured by Griffon Aerospace
- Platform for ISR missions, system tests, R&D, and payload development
- Flew in Canada successfully operating at 15,000 feet at -40 C in Feb 2018

Flight and Icing Cloud Conditions

- Cruise velocities and typical climbing AoA
- Temperature: -10 C (Glaze Ice) and -20 C (Rime Ice)
- Mean Volume Diameter (MVD): 15, 25, 50 µm
- Liquid Water Content (LWC): 0.5, 1.5, 2.0 g/m^3
- Exposure time: 10 minutes

*Cloud conditions were chosen to match corner cases from FAA Appendix C Icing Certification Criteria within IRT operating envelopes



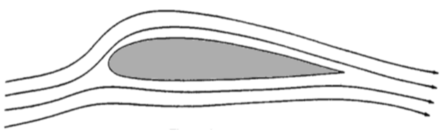


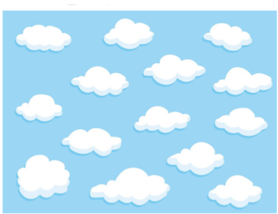
LEWICE3D Overview

- Research Code by NASA Glenn Research Center
- Simulate ice accretion on 3D aircraft surfaces (in Quasi-3D)

<u>Inputs</u>

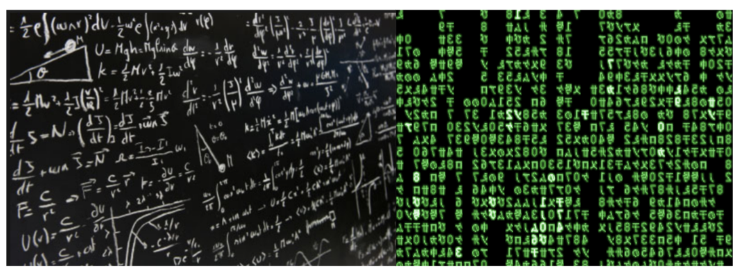
- Aerodynamic Flow Field
- Icing cloud conditions





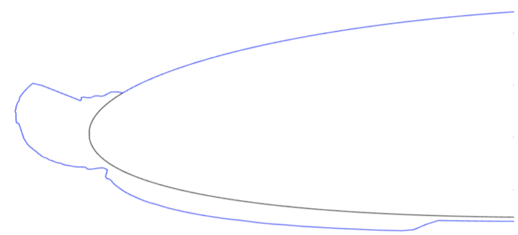
<u>Computational Module</u>

- Calculate approaching water droplet trajectories
- Calculate mass and energy transfer on surface
- Modeling freezing process in finite control volumes



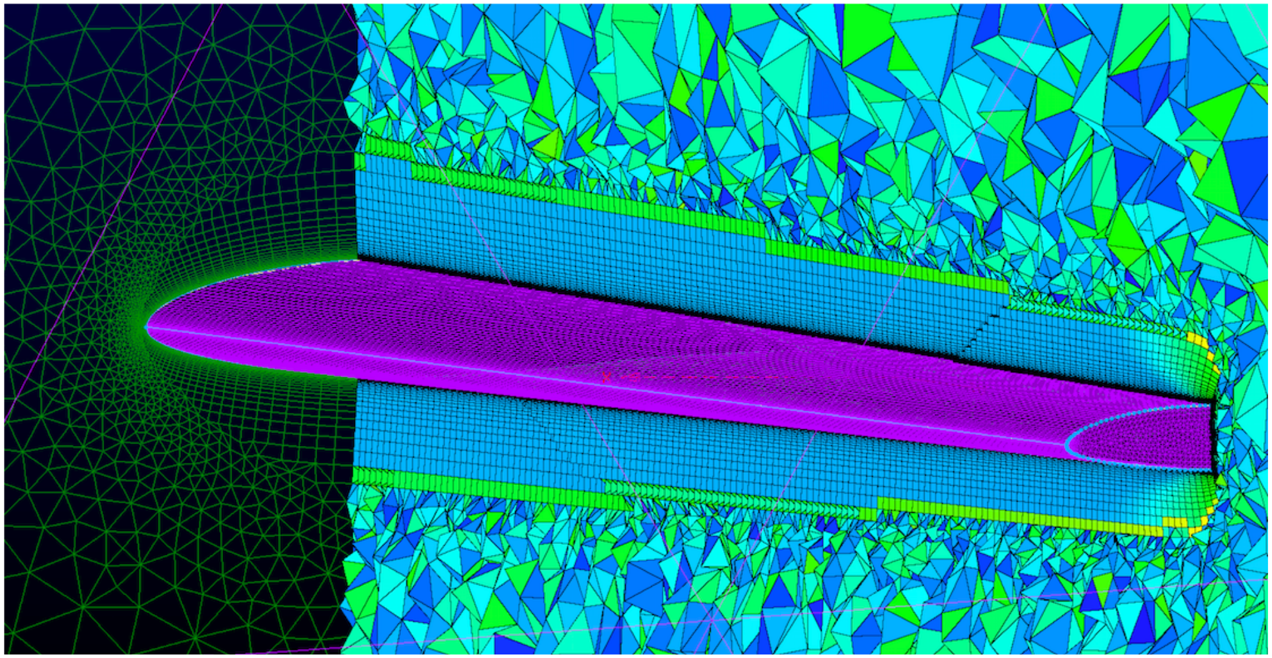
<u>Outputs</u>

- Ice shapes at 2-D section planes of interest

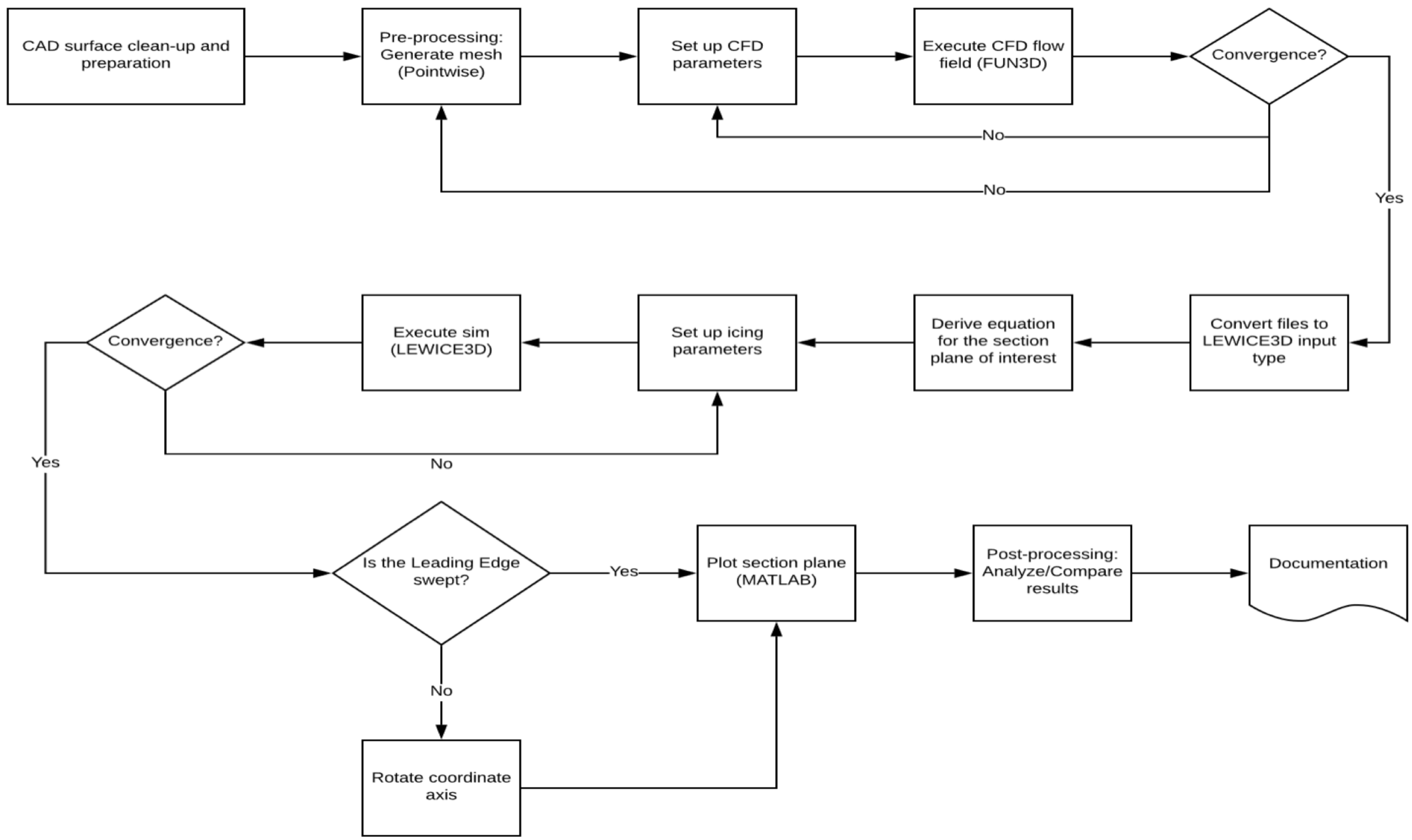


Meshing/CFD for Ice Accretion Simulations

- Same best practices as Low-Reynolds Number Incompressible Flow CFD Meshing
- Unstructured tetrahedrals in fluid domain with structured quads to capture surface resolution
- Boundary Layer Resolution
- Used NASA FUN3D Flow Solver



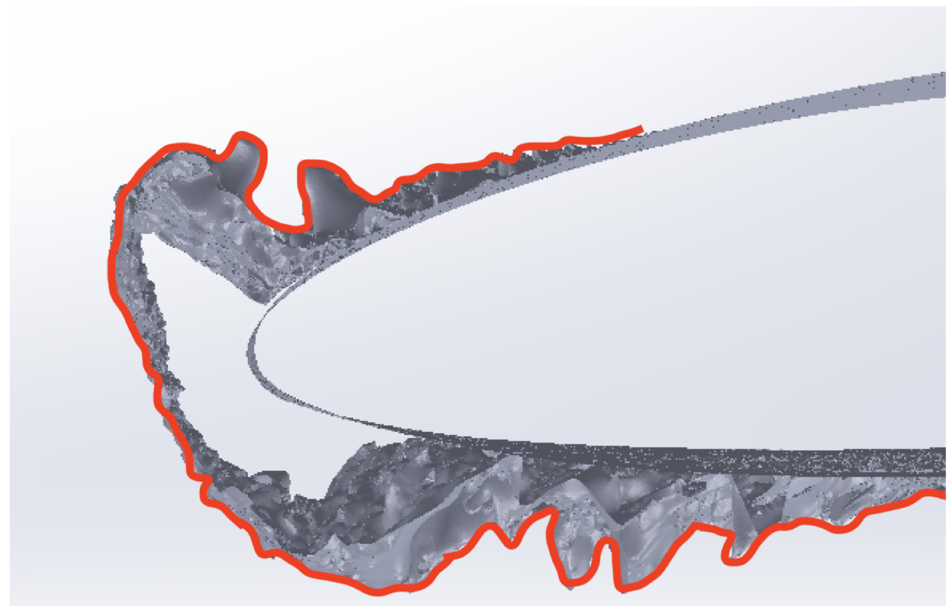
Methodology – Simulation of Ice Accretion



Methods of Quantitative Comparison

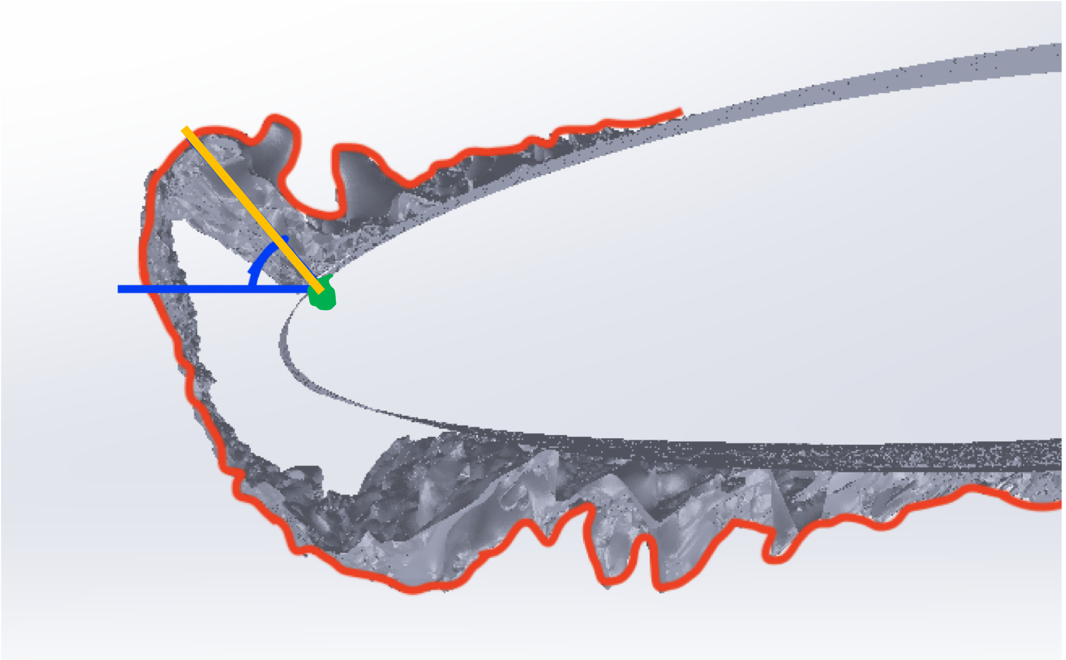
- Used high resolution robotic arm 3D scanner to capture experimental ice shape
- Maximum Combined Cross Sectional Area*

*For swept wings, perpendicular to LE



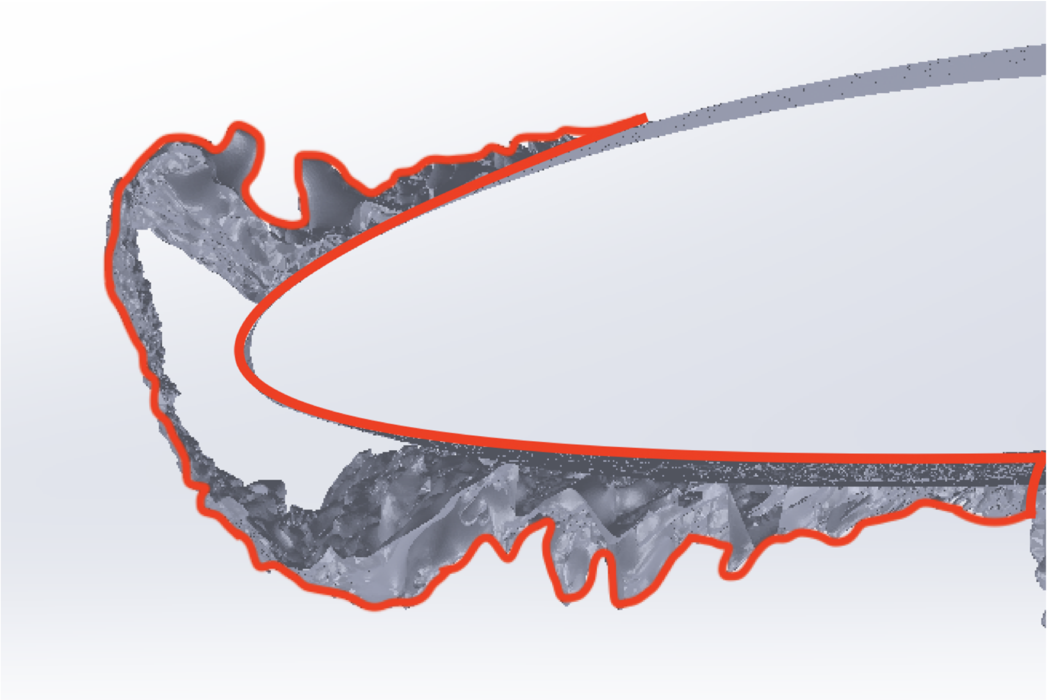
Methods of Quantitative Comparison

- Find largest horn perpendicular to aircraft surface
- Horn Location
- Horn Length
- Horn Angle



Methods of Quantitative Comparison

- Area/Volume of Ice
- Estimated Mass*

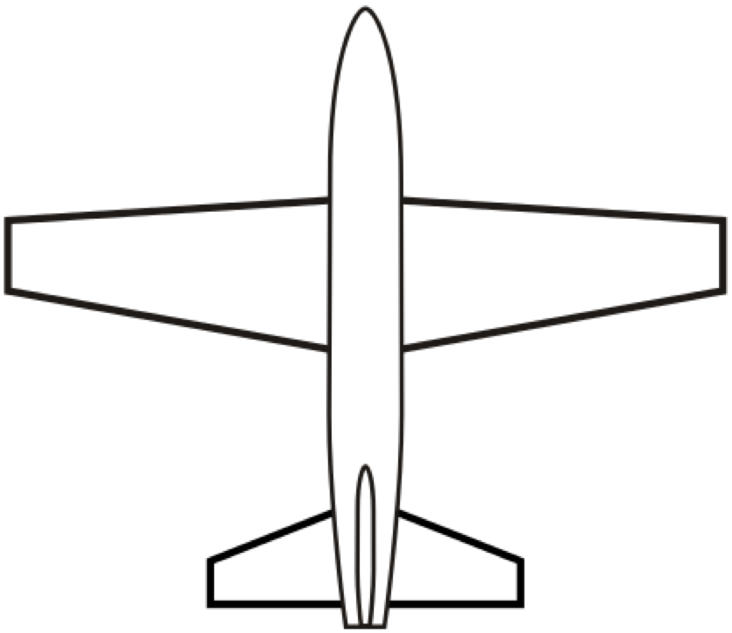


*Previous studies have used a density of 450 kg/m^3 to account for voids throughout the span

Tapered Wings

- Max Combined Cross Section fails
- Chord/thickness not consistent
- Limited to comparing single cut sections

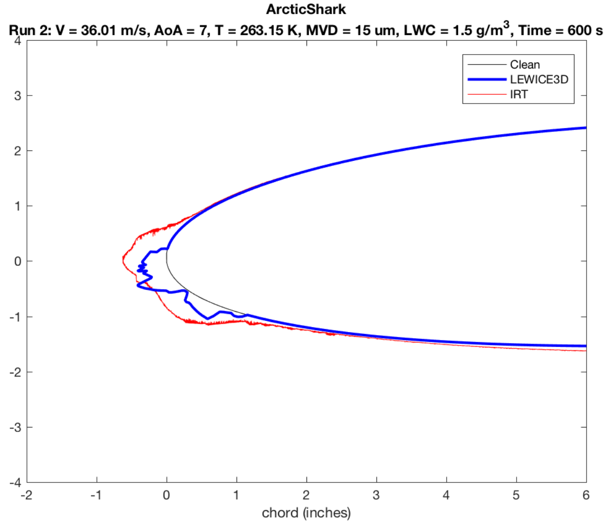
- SeaHunter and DataHawk faces this problem



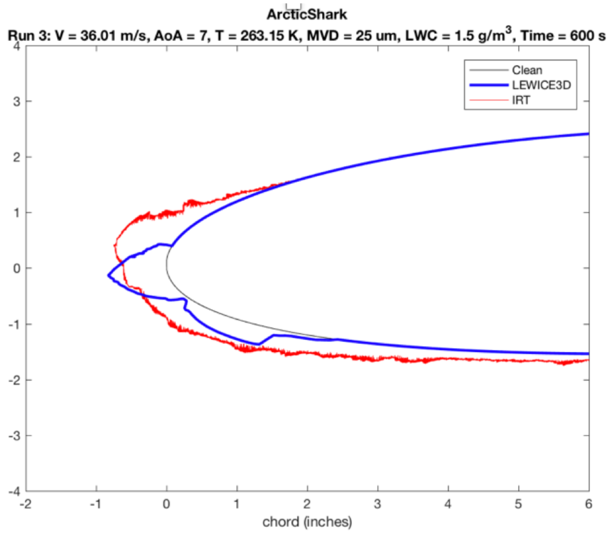
ArcticShark: Glaze Ice (-10 C), AoA = 7, V = 70 kts

Glaze Ice = Water droplets do not freeze immediately upon impact

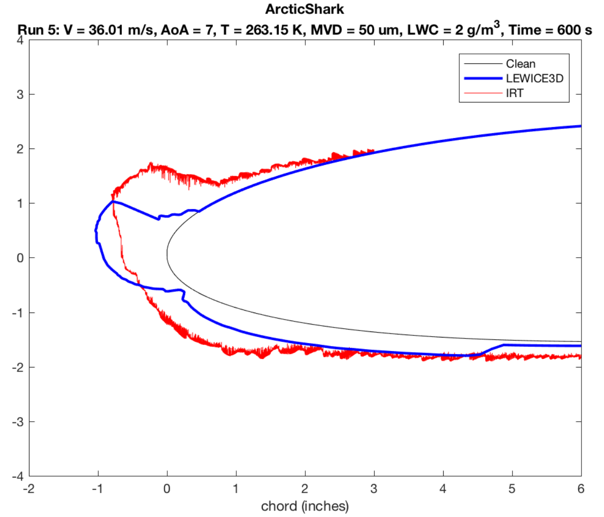
Experimental Data ▬▬▬ LEWICE3D Data ▬▬▬



MVD = 15 µm, LWC = 1.5 g/m3



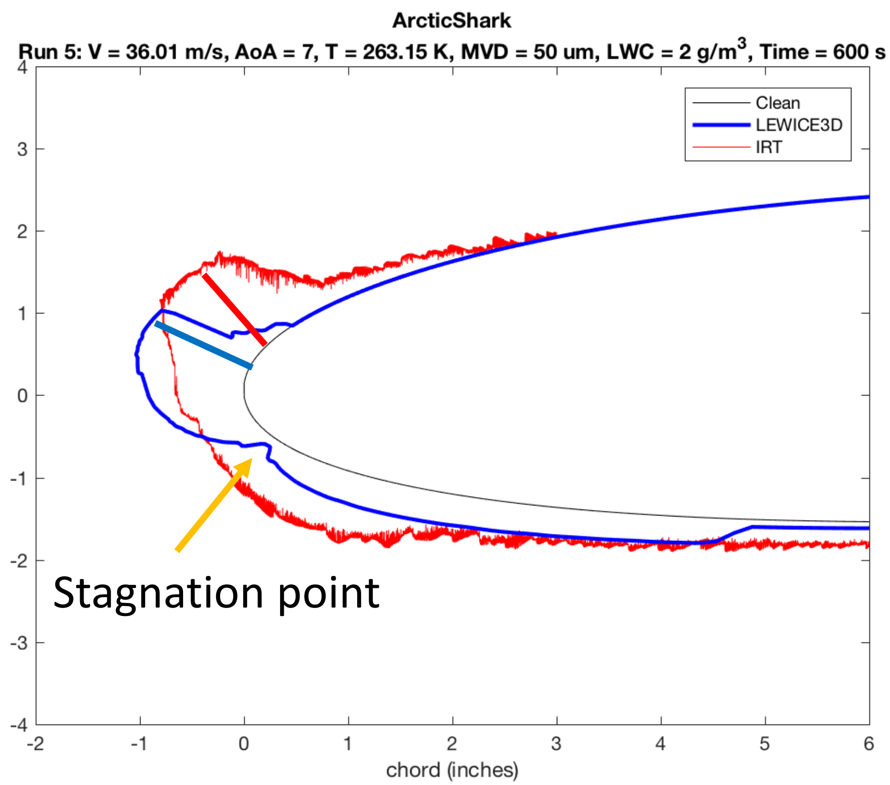
MVD = 25 µm, LWC = 1.5 g/m3



MVD = 50 µm, LWC = 2.0 g/m3

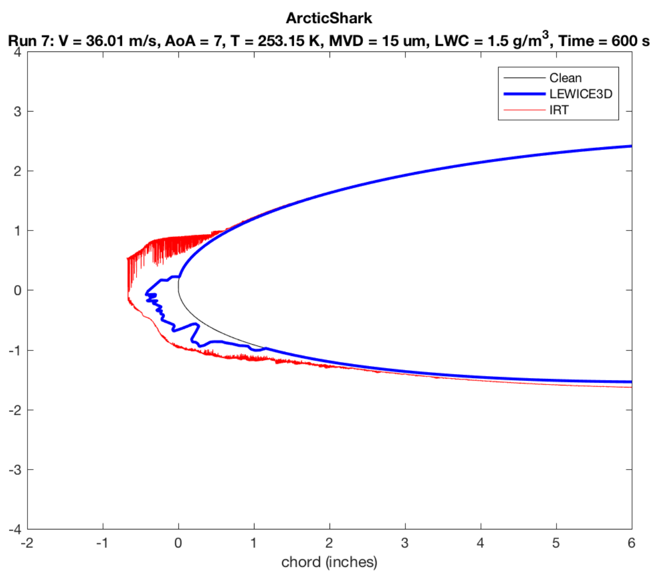
A Closer Look: Glaze Ice

- LEWICE3D has less ice volume (expected b/c IRT data is MCCS)
- LEWICE3D has lower horn angle
- Horn lengths are similar
- LEWICE3D has minimized icing on stagnation point

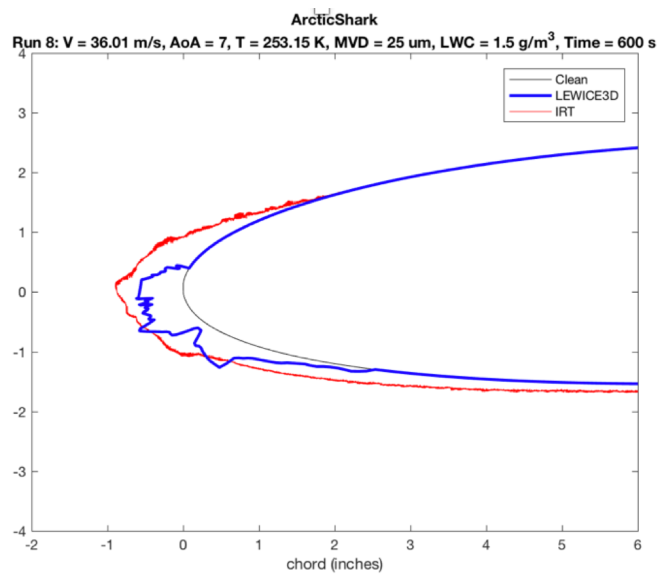


ArcticShark: Rime Ice (-20 C), AoA = 7, V = 70 kts

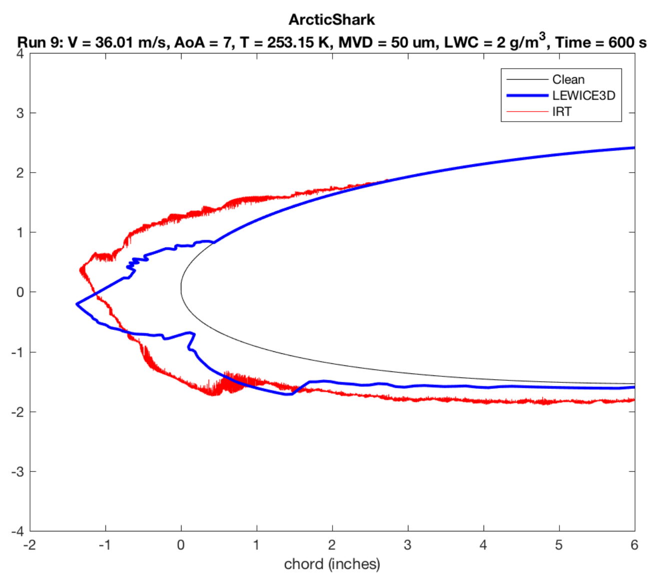
Rime Ice = Water droplets freeze immediately upon impact



MVD = 15 µm, LWC = 1.5 g/m3



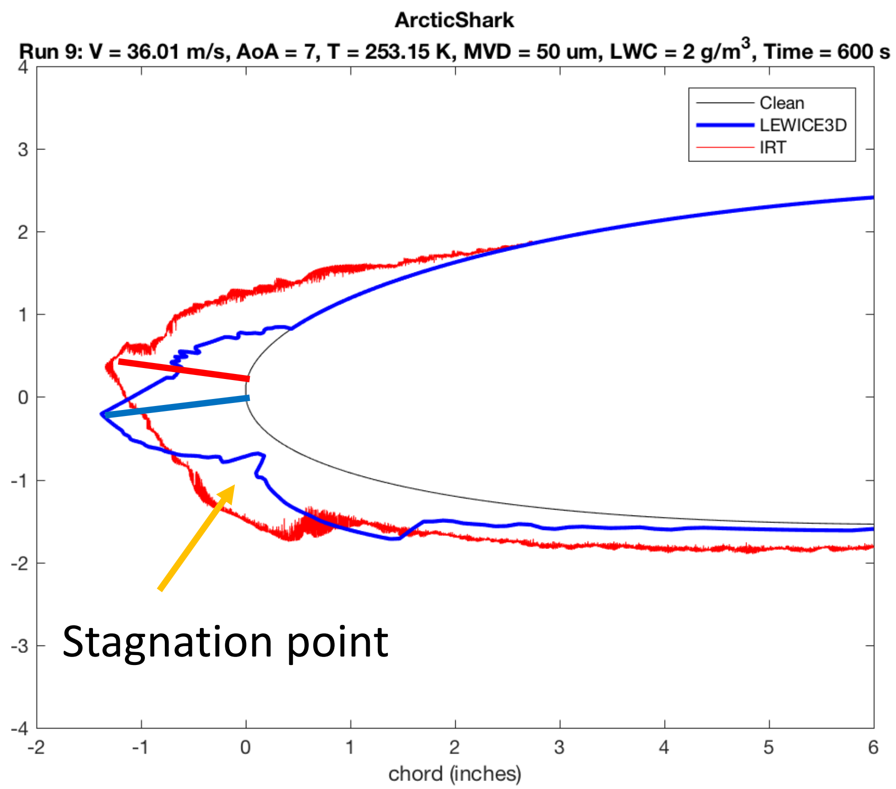
MVD = 25 µm, LWC = 1.5 g/m3



MVD = 50 µm, LWC = 2.0 g/m3

A Closer Look: Rime Ice

- LEWICE3D has less ice volume (expected b/c IRT data is MCCS)
- LEWICE3D has lower horn angle
- Horn lengths are similar
- LEWICE3D has minimized icing on stagnation point



Sources of Errors/Inconsistencies

- Assumed atmospheric pressure in LEWICE3D sims, IRT static pressures vary
- Have not done mesh convergence studies with icing simulations
- Assumed universal droplet size in LEWICE3D, IRT has a drop-size distribution
- IRT is not typically calibrated to low speeds
- LEWICE3D does not use a multi-time-step approach with updated flow fields
- Max Combined Cross Section is not exactly representative of full 3D ice shape
- Flow Angularity and Wall Effects in the IRT
- Surface roughness on test article

Future Research

- Further data post-processing (average cross section, compute volume, etc)
- GLENNICE Full 3D Ice Accretion Software Release in Late 2019
- Another Icing Tunnel Test in November 2018
- Multi-rotor aircraft
- Engine-on testing
- Aerodynamic testing of ice shapes in wind tunnel
- Wind tunnel testing of de-icing strategies (thermal de-icing, icephobic materials, mechanical de-icing)
- Ice sensors coupled with de-icing control systems
- Actual Flight Testing in Icing Conditions

Big Thanks To…..

- Robert Dahlgren, an amazing mentor
- Matthew Fladeland, interface with the science community
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- Jack Oldenburg and Seth Sederholm (IRT)
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- Christopher Penny for STAR-CCM+ support
- Alex Mazhari for aero analysis support

References

1. Fujiwara, G. and M. Bragg. 2017. 3D computational icing method for aircraft conceptual design. In: 9th AIAA Atmospheric and Space Environments Conference.
2. Potapczuk, M. and A.Broeren. 2017. An Integrated Approach to Swept Wing Icing Simulation. In: 7th European Conference for Aeronautics and Space Sciences.
3. Tim Baker, *“Mesh generation: Art or Science?”,* Progress in Aerospace Sciences 2005

Backup Slides

CFD Aerodynamic Flow Field

- Used NASA FUN3D Unstructured Flow Solver
- LEWICE3D uses flow field to solve ice growth calculation in one time-step
- Ideally, use multiple time-steps, updating the mesh and flow field every time
- LEWICE2D does this with 2D inviscid panel method
- 3D Mesh Adaptation and RANS (Viscous) 3D Flow Solution too computationally expensive
- This feature will be implemented in next-generation LEWICE3D (GLENNICE3D)

for every timestep
    calculate trajectories using flow field
    calculate ice shapes
    update mesh based on ice shapes
    calculate flow field on new mesh
repeat

CFD WorkFlow